

Petrochemistry and Tectonic Setting of the Phrao-Wiang Pa Pao Granitic Rocks, Chiang Mai, and Chiang Rai Provinces, Central Granitic Belt of Thailand

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Abstract

The Phrao-Wiang Pha Phao granitic rocks are crop out along Highway Number 1150 (Phrao-Wiang Pa Pao) in Chiang Mai and Chiang Rai provinces. The geologic investigation as field observation, lithology, petrography, geochemistry, and tectonic interpretation applied for this study. The least-altered 19 rock samples were collected and performed in stained rock slabs for modal analysis and standard thin sections for petrographic analysis. Based on the Quartz-Alkali Feldspar-Plagioclase diagram for plutonic rocks, the rock samples in the Phrao area are granodiorite, and one is biotite-monzogranite, while most of the rock samples in the Wiang Pa Pao area are biotite-monzogranite. The petrographic investigation for rock samples indicated that granitic samples have medium to coarse-grained and show porphyritic texture. The orthoclase phenocrysts are sitting in the groundmass and are composed of quartz, plagioclase, and orthoclase feldspar, with a minor amount of biotite, muscovite, apatite, zircon, titanite, and opaque minerals. The granitic samples can be classified as granodiorite to monzogranite, which is high-K calc-alkalic affinity and peraluminous S-type based on geochemistry. Based on the normative mineralogy calculation, the rock samples were composed mainly of normative quartz, plagioclase, and orthoclase, with minor corundum, hypersthene, magnetite, ilmenite, apatite, zircon, and chromite. The S-type granitoid supported by normative corundum and Na₂O/K₂O ratios less than 0.49 at Na₂O ranging from 1.53 - 2.35 wt %. Their tectonic setting of formation appears to be a post-orogenic environment (post-collisional granite) of the Sibumasu and the Indochina blocks. The Phrao Phrao-Wiang Pha Phao granitic rocks are a part of the Central Granitic Belt and are related to tin-tungsten deposits with rare earth elements.

Keywords: Phrao-Wiang Pa Pao Granites, Peraluminous, S-Type, High K-calc alkaline rock, Orogenic environment, Central Granitic Belt

Introduction

The granitic belts were important for ore deposits [1,2]. The granite in Thailand has been studied by many researchers and separated into 3 belts: Western, Central, and Eastern granitic belts based on their distribution and geochemistry [3-5].

The Western Granitic Belt (WGB) is distributed in western Thailand and along the Thai-Burma border. The rocks include granite, monzonite, and granodiorite. The WGB whole-rock geochemistry is ferroan, alkali-to alkali-calcic alkalic, peraluminous, and S-type affinity with small I-type pluton. The tectonic setting is a syn-collisional and within-plate environment that is formed by the sedimentary rock partial melting in a post-collisional setting [6,7]. The WGB is related to tin-tungsten (cassiterite-wolframite), precious metals, and rare earth elements (REE) minerals [1,2,8-10].

The Eastern Granitic Belt (EGB) is distributed in central to eastern Thailand along the Korat Plateau rim related to metal minerals such as ilmenite and magnetite. The EGB rocks are granite, granodiorite, and monzodiorite. The whole-rock geochemistry is calc-alkaline affinity, metaluminous, and I- to A-type granite affinity. Zircon U-Pb dating yields ages of 208 - 214 Ma (the Late Triassic) for granite bodies corresponding to the collision time of the Sibumasu and Indochina terranes, and some dates to 55 Ma is likely related to the collision time of the Indian and Eurasian continents [11-15]. The EGB is related to magnetite-cassiterite skarn, base metal sulfides with antimony [1,2,10].

The Central Granitic Belt (CGB) is the main granitoid in Thailand and occurs as a pluton and continuous north-south orientation and underlies almost all of northern-central and peninsular Thailand, the main range of Malaysia, and the Bangka, Singkep, and Tuju Islands of Indonesia. The CGB can be divided into the Eastern and the Western sub-belts. The Eastern sub-belt comprises the western Mae Chan pluton in Chiang Rai province, the Fang-Mae Suai-Wiang Pa Pao batholith in Chiang Mai province, and the Khuntan batholith in Lamphun province. The Western sub-belt consists of composite plutons in the Mae Sariang complex extending from Pai district, Mae Hong Son through Samoeng, Mae Chaem, and Hot districts and Doi Inthanon Mountains, Chiang Mai province, to the western part of Tak province. The granitoid rocks are generally coarse-grained but are variable in texture, ranging from abundant megacrysts to equigranular and mineralogy, from biotite-rich to biotite-muscovite-bearing and rarely green hornblende. The geochemistry of this pluton is largely sub-alkaline series, high-K calc-alkaline and peraluminous rock, and S-type affinity [16]. Although granitoids in this belt mostly have S-type affinity, the I-type with magnetite-series granitoids scattering found in Doi Mok and Doi Tung, Chiang Rai province and Doi Kio Lom, Pai district, Mae Hong Son province [17,18]. The absolute age of this granitic belt by $^{40}\text{Ar}/^{39}\text{Ar}$ dating is Late Triassic (220 - 180 Ma) for northern Thailand to Middle Jurassic, and Late Cretaceous to Middle Tertiary (80 - 50 Ma) for southern Thailand [3] and the U-Pb yielded age dating is Late Cretaceous (72 - 73 Ma) for northwestern Thailand [17,18]. The porphyritic granite zircon U-Pb age dating was done by [4] in the Mae Suai area, Chiang Rai province in the north of the Phrao-Wiang Pa Pao area and was 220 ± 1 Ma (late Triassic). In-situ Th-U-total Pb dating of monazite in the Inthanon metamorphic rocks indicates at least 2 metamorphic events: The first event is a widespread medium P-T regional metamorphic phase in the Early Jurassic (~185 Ma) that is related to abundant plutonism during Sukhothai-Sibumasu collision and the second event is a younger overprint of unclear grade (low to high T assemblages are found) but significant spatial extent in the Early Paleocene (~60 Ma) that does not appear to be connected with regional plutonic activity and might be related to large scale shearing as seen in the Mae Ping and 3 Pagoda shear zones [19]. The Triassic porphyritic granite in the Dan Chang area, Suphan Buri province comparable to the S-type granite of the CGB, resulting from syn-collisional crustal thickening and subsequent post-collision after the closure of the Paleotethyan during the Late Triassic with the crystallization Pressure-Temperature (P-T) conditions are 3.3 - 3.8 kbar and 571 - 656 °C, and calculated intrusion depths of 12 - 14 km [20]. The CGB is related to tin-bearing s-type granite and endogenous vein and skarn replacement scheelite and fluorite deposits with some tin and local antimony in the north Thailand Migmatitic Province [1,2,10].

The study area is located in northern Thailand between the latitude of 19°16'' to 19°22' and longitude of 99°11' to 99°31' in the area of the eastern part of Phrao district, Chiang Mai province and western part of Wiang Pa Pao district, Chiang Rai province that is Mae Suai-Wiang Pa Pao batholiths which is a part of the CGB. Geological data of the study area and vicinity complies by Baum and Hahn [21] and Department of Mineral Resources [22]. The studied area was covered by Silurian-Devonian metamorphic rocks (SD), Carboniferous sedimentary rocks (C), Quaternary sediments (Qa) and intruded by late Triassic igneous rock (Trgr) (**Figure 1**). Silurian-Devonian sedimentary rocks are phyllite, carbonaceous phyllite, and siliceous phyllite. Carboniferous sedimentary rocks are conglomerate, sandstone, shale, chert, calcareous conglomerate, and slate. The late Triassic igneous rocks are biotite-muscovite-tourmaline granite and granodiorite. Quaternary sediments are Quaternary terrace sediments and Quaternary alluvial sediments. It is composed of gravel, sand, silt, and clay. The 19 granitic rock samples were collected from road-cut outcrop along highway number 1150 from Phrao district, Chiang Mai province and Wiang Pa Pao district, Chiang Rai province, between kilometers 55 - 76, for these study petrography and geochemistry. The purposes of this study are to clarify the rock-forming mineral composition, geochemistry of the granitic rocks, the tectonic setting of emplacements and economic minerals relation.

Materials and methods

Sample collection

The field investigation was done along highway number 1150 (Phrao-Wiang Pa Pao). The least-altered 19 samples were collected from road-cut outcrop between kilometers 55 - 76. The samples divided into 2 groups based on their occurrence as the Phrao area (sample nos. PW01, PW02, PW03, PR04, PR05, PR06, PR07, PR09, PR10, PR12, PR13, PR14) and the Wiang Pa Pao area (sample nos. PW04, PW05, PW06, PW07, PW08, PW09, PW10) (**Figure 1**).

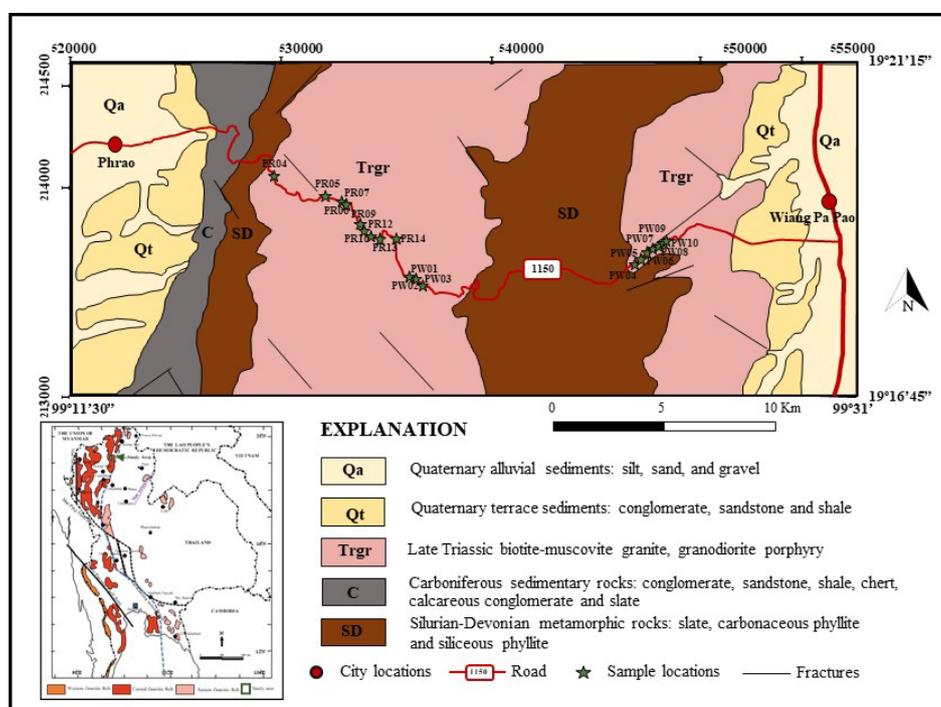


Figure 1 The enlarged map of the study area (see inset) illustrates the distribution of granitic rock in the north of the eastern sub-belt of Central Granitic Belt (Modified from Geological Map of Northern Thailand 1:250000 sheet 3 (Phayao), [21] and [22]).

Sample preparation and selection

The granitic rock samples were prepared for standard thin sections for petrographic investigation, stained rock slabs for modal analysis for lithology investigation, and powdered samples for whole-rock chemical analysis.

The standard thin sections were made by cutting and polishing rock samples until approximately 0.03 mm thickness. The mineral and texture study and least-altered sample selection were done by petrographic investigation. The least-altered samples selection generally excluded those with the extensive development of mesoscopic domains of secondary minerals such as quartz resulting from silicification, epidote minerals and chlorite, well-developed foliation or mineral layering, abundant vugs or druses, xenocrysts, and xenoliths and quartz, epidote, or calcite veining and patches totaling more than 5 modal %.

The stained rock slabs for modal analysis were made by the weathering surfaces cutting before making slabs and soaking the slabs in hydrofluoric acid (HF) and sodium cobaltinitrite solution ($\text{CoN}_6\text{Na}_3\text{O}_{12}$). The proportions of mineral compositions were used for rock nomenclature by modal analysis on stained rock slabs.

The sample powder was performed by cutting off the weathering surfaces of the samples, splitting into conveniently sized fragments, and crushing into small chips using a Rocklabs Hydraulic Splitter/Crusher. The cleaned rock chips were quarters, and approximately 50 - 80 g sample rock chips were pulverized for a few minutes by a Rocklabs Tungsten-Carbide Ring Mill. The fusion discs and pellets for whole-rock chemical analysis were performed from powder samples.

Analytical technique for geochemistry

The sample powders were prepared for major element oxides, trace elements, and loss on ignition (herein LOI) analysis. Major element oxides (SiO_2 , TiO_2 , Al_2O_3 , total iron (FeO and Fe_2O_3) as FeO^* , MnO , MgO , CaO , Na_2O , K_2O , and P_2O_5) and some certain trace elements (Ba, Rb, Sr, Y, Zr, Nb, Ni, V, Sc, Cr and Th) were carried out using Philips Magix PRO X-ray fluorescence (XRF) spectrometer (wavelength dispersive system). The rock standards were the USGS geochemical reference materials, AGV-2, BCR-2, BHVO-2G, BIR-1a, DTS-2b, DNC-1a, W-2a, GSP-2, QLO-1a, RGM-2 and STM-2. These chemical species were measured from fusion discs for the major element oxides and pressed powder for trace elements. The fusion discs prepared by melting 0.7 g sample powder, 7 g spectromelt (di-lithium tetraborate; $\text{Li}_2\text{B}_4\text{O}_7$), and 0.375 g lithium bromide (LiBr) and pressed powders prepared by mixing and pressing 6 g sample powder and 0.3 g XRF MULTI-MIX PXR-200. Ignition loss was analyzed by heating approximately 1 g of powdered samples at 1,000 °C for 8 h [23]. The least-altered samples were repeat selections from geochemical data plots on alteration box plots [24] so that the 19 least-altered granitic rock samples were suitable for geochemical interpretation. All the described procedures were done at the Department of Geological Sciences, Faculty of Science, Chiang Mai University.

Results and discussion

Lithology and petrographic investigation

The granitic rocks are grey-white or light grey in the outcrop and have a porphyritic texture in the hand specimens. The petrographic investigation for rock samples (**Figure 2**) indicated that granitic samples have a medium to coarse-grained and porphyritic texture. The phenocrysts are alkaline feldspar phenocrysts that sit in the groundmass. Groundmass is composed largely of quartz, plagioclase, and potassium feldspar, with a minor amount of biotite, muscovite, apatite, zircon, titanite, and opaque minerals. Potassium feldspar phenocrysts and groundmass are orthoclase and microcline. It shows subhedral outlines and perthitic texture and are moderate to highly altered to sericite and clay minerals. Quartz groundmass shows anhedral

crystals, rounded edges, and embayed outlines. Plagioclase groundmass is anhedral to subhedral outlines and shows myrmekitic texture. It is moderate to highly altered to sericite and clay minerals. Biotite shows anhedral to subhedral and brown color. It is highly altered to chlorite and epidote minerals. The nomenclature based on rock-forming mineral constituents indicated that it is monzogranite to granodiorite. Modal analysis performed on the stained rock slabs reveals that the studied least-altered samples have relative proportions of quartz, potassium feldspar, and plagioclase (**Table 1**). The nomenclature of the rocks based on the Quartz-Alkali Feldspar-Plagioclase (QAP) diagram for plutonic rocks of [25] (**Figure 3**) shows that all of the rock samples in the Phrao area are granodiorite, except sample nos. PW01 is biotite-monzogranite, while most of the samples in the Wiang Pa Pao area are biotite-monzogranite.

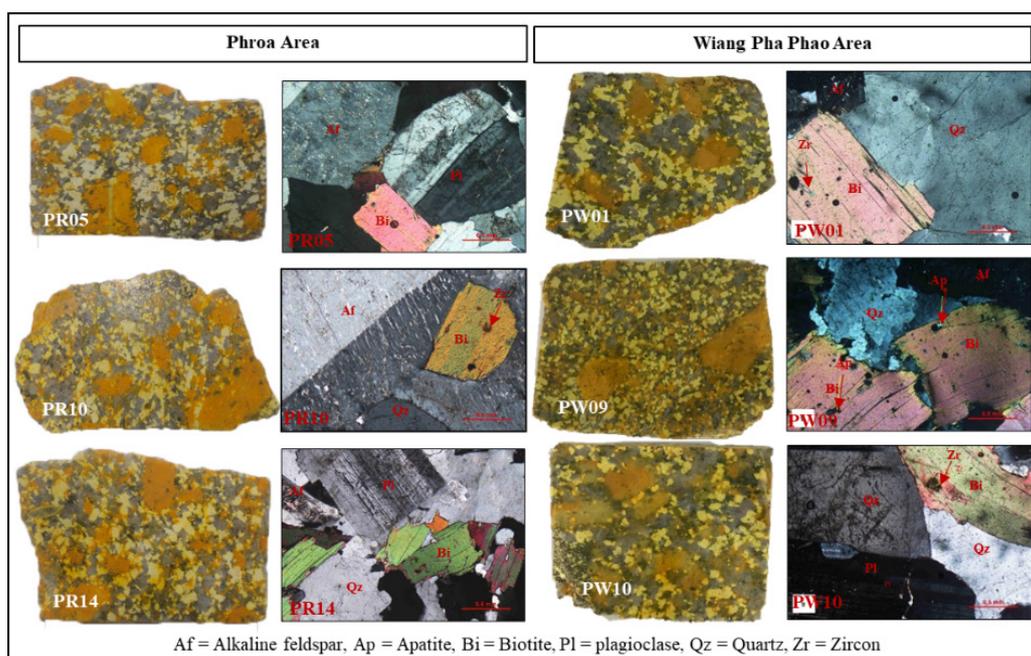


Figure 2 Stained rock slabs and photomicrograph of granodiorite in the Phrao area and monzogranite in the Wiang Pa Pao area.

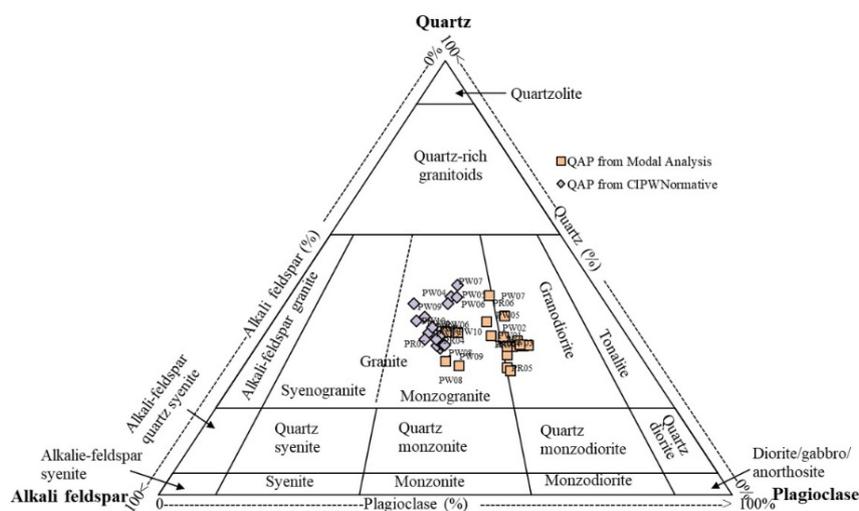


Figure 3 QAP diagram plot by modal analysis and CIPW Normative ratios.

Table 1 Major element oxides, some certain trace elements, and modal analysis minerals of the studied least-altered granitic rocks. CIPW normative minerals were calculated, according to the principles of geochemistry.

Wiang Pha Phao Area										
Sample no.	PW01	PW02	PW03	PW04	PW05	PW06	PW07	PW08	PW09	PW10
Granite type	Bi-MGr	Grano diorite	Grano diorite	Grano diorite	Bi-MGr	Bi-MGr	Bi-MGr	Bi-MGr	Bi-MGr	Bi-MGr
Major element oxide (wt %)										
SiO ₂	71.60	69.17	69.98	71.69	72.48	72.32	73.77	70.59	73.23	71.70
TiO ₂	0.48	0.57	0.43	0.53	0.43	0.41	0.38	0.42	0.40	0.39
Al ₂ O ₃	14.36	15.30	15.68	14.26	14.46	14.74	14.13	14.92	14.03	14.88
FeO*	2.94	3.50	2.85	3.30	2.76	2.56	2.46	2.61	2.52	2.55
MnO	0.01	0.01	0.00	0.03	0.02	0.01	0.00	0.02	0.01	0.01
MgO	1.91	2.42	1.95	2.27	1.84	1.69	1.64	1.77	1.47	1.64
CaO	1.96	2.32	2.26	2.34	2.31	2.27	2.18	2.07	1.64	1.82
Na ₂ O	1.70	1.77	1.74	1.65	1.82	1.78	1.77	2.35	1.54	1.67
K ₂ O	4.85	4.73	4.95	3.73	3.70	4.06	3.50	5.07	4.98	5.19
P ₂ O ₅	0.19	0.23	0.16	0.21	0.18	0.17	0.16	0.18	0.17	0.16
LOI	0.76	0.78	0.84	1.23	0.76	0.79	0.77	1.01	0.69	0.78
Original Sum	101.36	102.16	101.29	102.17	100.94	103.24	101.60	101.59	99.94	100.06
Trace elements (ppm)										
Ba	656.14	709.35	881.83	475.41	475.85	502.49	469.19	753.84	639.23	524.36
Rb	307.29	251.99	264.64	249.15	247.63	268.06	243.49	254.1	323.42	309.73
Sr	157.94	156.48	211.33	171.08	130.34	154.11	128.26	175.7	133.82	118.6
Y	105.92	76.25	80.16	85.56	79.53	86.77	87.05	77.19	101.14	101.55
Zr	224.4	208.3	184.28	246.7	202.76	205.29	200.05	191.18	196.5	183.54
Nb	15.92	17.6	14.51	17.11	16.23	16.42	16.17	16.63	19.42	13.97
Ni	32.05	38.28	31.31	34.95	27.48	31.21	44.09	32.76	32.52	31.65
Cr	69.92	95.63	68.29	73.95	87.51	53.97	65.07	60.77	34.17	49.27
V	87.63	93.31	86.56	93.31	81.53	79.63	77.32	81.19	78.57	72.62
Sc	5.64	8.3	7.34	7.09	5.64	9.29	7.01	5.72	6.42	5.64
Th	41.46	28.91	24.84	46.27	36.47	33.48	30.91	33.39	37.59	33.32
Modal analysis										
Quartz (Q)	35.50	28.80	33.00	31.80	37.50	32.00	33.30	28.50	23.50	27.50
Alkali feldspar (A)	27.30	24.00	25.00	23.50	21.30	30.00	23.50	35.50	36.90	23.30
Plagioclase (P)	30.50	42.00	40.00	41.00	39.80	35.00	39.50	31.00	31.00	39.50

Wiang Pha Phao Area										
Accessory minerals	6.80	5.30	2.00	3.80	1.50	3.00	3.80	5.00	8.60	9.80
CIPW normative										
Quartz	36.07	31.83	32.58	39.20	40.07	39.02	42.95	30.33	39.44	35.73
Plagioclase	22.92	25.04	24.94	24.19	25.74	25.27	24.80	29.03	20.11	22.14
Orthoclase	29.17	28.53	29.98	22.41	22.23	24.43	21.05	30.54	29.94	31.11
Corundum	3.09	3.48	3.58	3.70	3.61	3.61	3.76	2.10	3.42	3.50
Hypersthene	5.18	7.41	6.02	7.00	5.04	4.60	4.49	4.82	4.05	4.51
Ilmenite	0.91	1.08	0.82	1.01	0.82	0.78	0.72	0.80	0.76	0.74
Magnetite	2.13	2.03	1.65	1.91	2.00	1.86	1.78	1.88	1.83	1.84
Apatite	0.44	0.53	0.37	0.51	0.42	0.39	0.37	0.42	0.39	0.37
Zircon	0.04	0.04	0.03	0.04	0.04	0.04	0.04	0.04	0.04	0.03
Chromite	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.01
Phroa Area										
Sample no.	PR04	PR05	PR06	PR07	PR09	PR10	PR12	PR13	PR14	
Granite type	Grano diorite									
Major element oxide (wt %)										
SiO ₂	65.24	64.56	66.53	67.12	66.29	65.87	65.34	66.68	66.22	
TiO ₂	0.58	0.60	0.57	0.55	0.52	0.60	0.59	0.53	0.56	
Al ₂ O ₃	19.20	19.74	17.99	17.88	18.34	18.00	18.77	17.94	18.49	
FeO*	3.50	3.64	3.52	3.37	3.28	3.77	3.81	3.31	3.38	
MnO	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	
MgO	2.56	2.65	2.52	2.46	2.34	2.66	2.72	2.41	2.40	
CaO	2.49	2.46	2.45	2.27	2.50	2.55	2.28	2.40	2.40	
Na ₂ O	1.68	1.68	1.72	1.61	1.78	1.80	1.53	1.97	1.72	
K ₂ O	4.52	4.44	4.47	4.49	4.74	4.54	4.75	4.54	4.60	
P ₂ O ₅	0.22	0.24	0.23	0.23	0.20	0.21	0.20	0.21	0.23	
LOI	1.01	0.81	0.62	0.84	0.71	0.72	0.94	0.83	0.73	
Original Sum	96.07	95.28	96.88	98.56	93.30	99.97	100.54	95.16	97.34	
Trace elements (ppm)										
Ba	604.52	568.6	569.76	581.17	600.21	477.26	595.24	584.28	643.02	
Rb	267.55	275.09	242.46	255.73	268.34	238.23	285.27	273.46	266.84	
Sr	155.46	151.77	147.48	145.26	160.39	118.11	133.45	162.19	167.52	
Y	84.17	91.63	76.47	78.05	85.42	71.41	93.82	85.78	86.31	
Zr	243.33	243.51	218.92	216.28	211.62	183.62	246.69	222.92	222.62	
Nb	19.17	19.46	15.42	16.84	16.27	17.47	14.04	17.74	16.07	

Wiang Pha Phao Area									
Ni	43.65	40.07	37.79	33.67	38.21	34.22	41.84	40.54	39.22
Cr	70.31	137.85	92.88	124.9	82.37	90.3	92.55	111.75	93.57
V	96.42	103.46	89.43	92.15	90.69	90.35	95.79	98.61	91.83
Sc	8.17	6.55	7.73	7.65	8.3	7.3	7.82	4.35	5.64
Th	39.08	35.97	29.4	28.12	34.37	30.02	37.35	27.98	31.98
Modal analysis									
Quartz (Q)	41.03	48.05	43.48	38.51	39.00	44.64	38.01	39.19	40.53
Alkali feldspar (A)	19.09	11.41	17.10	18.97	19.06	14.58	18.13	10.95	13.31
Plagioclase (P)	36.18	34.53	35.36	35.06	37.24	34.52	34.50	34.29	39.05
Accessory minerals	3.70	6.01	4.06	7.47	4.69	6.25	9.36	15.56	7.10
CIPW normative									
Quartz	28.68	28.33	30.12	31.77	28.58	28.27	28.85	28.59	29.30
Plagioclase	25.19	24.91	25.26	23.44	26.21	26.54	22.94	27.12	25.01
Orthoclase	27.22	26.67	26.91	27.03	28.52	27.25	28.64	27.22	27.63
Corundum	7.44	8.19	6.32	6.70	6.11	5.92	7.36	5.81	6.72
Hypersthene	7.76	8.00	7.65	7.43	7.15	8.15	8.33	7.54	7.51
Ilmenite	1.10	1.14	1.08	1.04	0.99	1.14	1.12	1.01	1.06
Magnetite	2.03	2.12	2.04	1.96	1.90	2.19	2.22	2.13	2.17
Apatite	0.51	0.56	0.53	0.53	0.46	0.49	0.49	0.49	0.53
Zircon	0.04	0.04	0.04	0.04	0.04	0.03	0.04	0.04	0.04
Chromite	0.01	0.03	0.01	0.03	0.01	0.01	0.01	0.03	0.01

Whole-rock chemical analysis

Major element oxides and some certain trace elements of the least-altered Phrao-Wiang Pa Pao granitic samples are reported in **Table 1**. Major element oxide data have a variable composition with SiO₂ ranging from 64.56 to 73.77 wt. %, TiO₂ ranging from 0.38 to 0.60 wt. %, FeO* ranging 2.46 to 3.81 wt. %, CaO ranging from 1.64 to 2.55 wt. %, MgO ranging from 1.47 to 2.72 wt. %, MnO ranging from 0 to 0.03 wt. %, P₂O₅ ranging from 0.16 to 0.24 wt. %, Al₂O₃ ranging from 14.03 to 19.74 wt. %, K₂O ranging 3.50 and 5.19 wt. % and Na₂O ranging from 1.53 to 2.35 wt. %. Total alkali (Na₂O+K₂O+CaO) content ranging from 7.71 to 9.49 wt.%. The trace elements data have a variable composition with Cr ranging from 34.17 - 137.85 ppm, Nb ranging from 13.97 to 19.46 ppm, Y ranging from 71.41 to 105.92 ppm, Ni ranging from 27.48 to 44.09 ppm, Zr ranging from 183.54 to 246.70 ppm, Sc ranging from 4.35 to 9.29 ppm, Sr ranging from 118.11 to 211.33 ppm, Ba ranging from 469.19 to 881.83 ppm, Rb ranging from 238.23 to 323.42 ppm, V ranging from 72.62 to 103.46 ppm, and Th ranging from 24.84 to 46.27 ppm.

The alteration box plot [24] is a graphical representation that uses 2 alteration indices: the Ishikawa alteration index (AI) (horizontal axis) and the chlorite-carbonate-pyrite index (CCPI) (vertical axis). AI is the index that involves the breakdown of sodic plagioclase and volcanic glass and their replacement by

sericite and chlorite. CCPI is the index involves the 3 hydrothermal minerals chlorite, Fe-Mg carbonate (dolomite, ankerite, or siderite), and pyrite, magnetite, or hematite and is strongly affected by magmatic fractionation and primary compositional variations in the volcanic rocks. The alteration box plot was applied to define least-altered intrusive rock samples in this research that indicated primitive magma. The oxides, in terms of weight %, were used to calculate the AI (1) and CCPI (2), following the equations.

$$AI = (100(MgO+K_2O))/(FeO+K_2O+MgO+Na_2O) \quad (1)$$

$$CCPI = (100(FeO+MgO))/(FeO+K_2O+MgO+Na_2O) \quad (2)$$

The results show that the studied samples lie well within the limits of least-altered intermediate to felsic rocks of Large *et al.* [24] as shown in **Figure 4**. The least-altered samples were suitable for genesis interpretation.

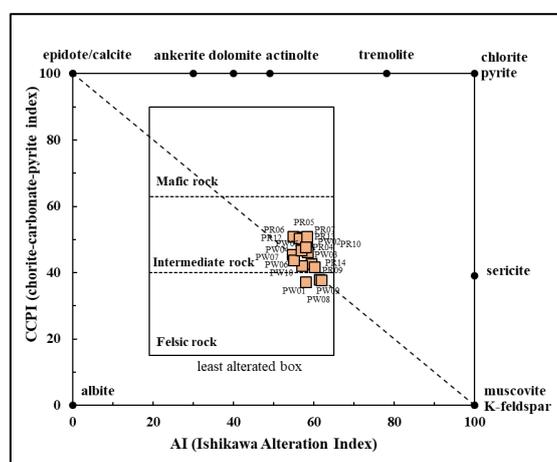


Figure 4 Alteration box plot showing the least altered Phrao-Wiang Pa Pao Granites.

The Cross, Iddings, Pirsson, and Washington (CIPW) normative mineralogy calculation [26] used major element oxides and trace elements concentrations to calculate the ideal magmatic crystallization minerals quantitation based on magma conditions were anhydrous at low pressure. As a result, all rock samples were composed mainly of normative quartz, plagioclase, and orthoclase, with minor corundum, hypersthene, magnetite, ilmenite, apatite, zircon, and chromite (**Table 1**). In addition, normative minerals of all samples are compositionally classified based on the QAP diagram for plutonic rocks of Streckeisen [25] as monzogranite (**Figure 3**). Based on the geochemical concentration indicated least-altered granitic rocks classified as granodiorite (sample no. PW02, PW03, PW04, PR04, PR05, PR06, PR07, PR09, PR10, PR12, PR13, and PR14) and monzogranite (sample nos. PW01, PW05, PW06, PW07, PW08, PW09, and PW10), and the most of studied rocks appear to be in the fields of sub alkaline or tholeiite series based on total alkalis against silica plot [27,28] (**Figure 5(a)**). In addition, the normative cation calculation was applied for the least-altered felsic rocks, and normative cation was classified based on the cation proportion diagram for plutonic rocks of De la Roche [29] as granodiorite (**Figure 5(b)**).

The geochemical characterization of the Phrao-Wiang Pa Pao granitoids is based on 3 variables: modified alkali-lime index (MALI) (Na_2O+K_2O-CaO), $Fe^* [FeO(t)/(FeO(t)+MgO)]$, and the aluminium saturation index (ASI). All of the samples of the Phrao granites are high-K calc-alkaline affinity dacite, and the Wiang Pa Pao granites are high-K calc-alkaline to calcic affinity rhyolite on the SiO_2-K_2O diagram plot

[30] (**Figure 6(a)**) while the all of samples are calc-alkaline to calcic affinity on the SiO₂-MALI plot [31] (**Figure 6(b)**). All of the rocks are calc-alkaline rocks on the FeO(total)-Na₂O+K₂O-MgO diagram plot [28] (**Figure 7(a)**), and magnesian rocks of the SiO₂-FeO(total)-MgO diagram [32] as shown in **Figure 7(b)**). The ASI plot (**Figure 8**) designated as peraluminous rocks in molar ratios Aluminum versus sodium and potassium (A/NK) (2.01 - 3.23) versus A/CNK (1.57 - 2.30) discrimination diagram [33-35]. The Harker variation diagram is the relationship between major element oxides and trace elements and SiO₂ that interprets the magma crystallization of samples. The correlation analysis determines the relation of samples (**Figure 9**). The correlation coefficient (r) values of Al₂O₃, TiO₂, MgO, FeO*, CaO, and P₂O₅ are -0.98, -0.88, -0.92, -0.88, -0.70 and -0.80, respectively that strong to very strong negative correlation. The r values of Na₂O and K₂O are 0.61 and 0.66, which show a strong positive correlation, and -0.58 and -0.49a, which show moderate negative correlation. Among trace elements, V, Cr, Ni, Zr, Nb, and Sc show a moderately to strong negative correlation with the r values are -0.81, -0.71, -0.54, -0.47, -0.16 and -0.16, respectively, while Y and Rb depict a significant positive correlation with the r values are 0.30 and 0.19.

Furthermore, the samples are plotted in the field of S-type granite in the Na₂O-K₂O (**Figure 10(a)**) and the K₂O-FeO(total) (**Figure 10(b)**) diagrams of Chappell and White [36]. The tectonic setting of formation is in the field of the boundary between ocean ridge granite, within-plate granite, and ocean ridge granite from the anomalous ridge in Y vs Nb (**Figure 11(a)**). Moreover, the tectonic setting plot of Rb against Nb+Y diagrams (**Figure 11(b)**) after Pearce [37] implies that it is within plate granite (post-collisional granite).

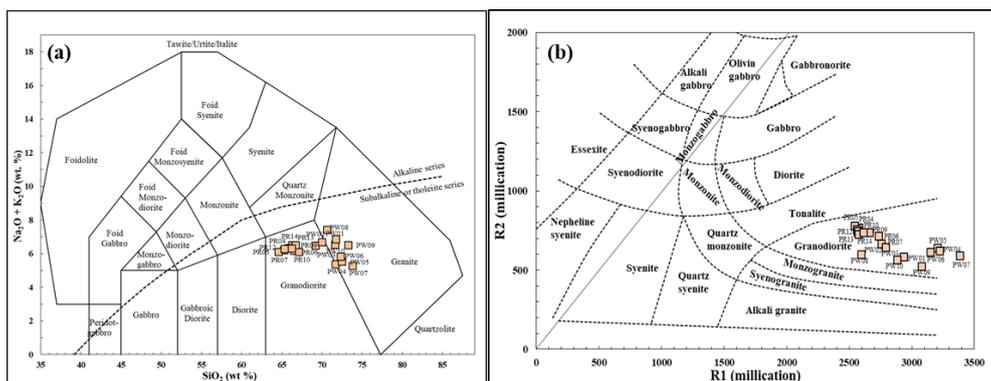


Figure 5 The discrimination diagrams of the Phrao-Wiang Pa Pao Granites (a) total alkali versus silica and (b) cation proportion.

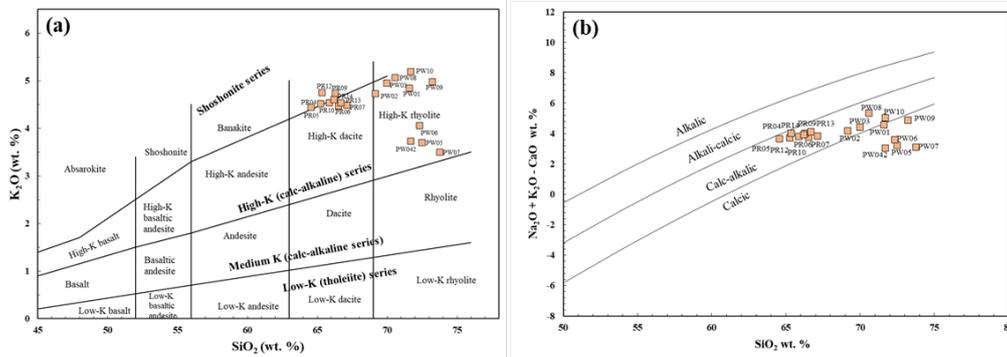


Figure 6 The discrimination diagrams of the Phrao-Wiang Pa Pao Granites (a) SiO₂ versus K₂O diagram with compositional domains of the different calc-alkaline series and (b) SiO₂-Na₂O-K₂O-CaO diagram.

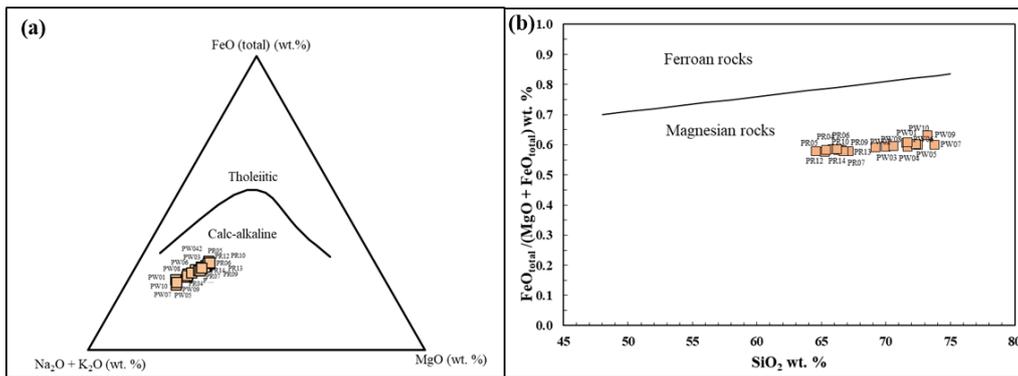


Figure 7 The discrimination diagrams of the Phrao-Wiang Pa Pao Granites (a) FeO(total) - Na₂O+K₂O - MgO and (b) SiO₂-FeO(total)-MgO diagrams.

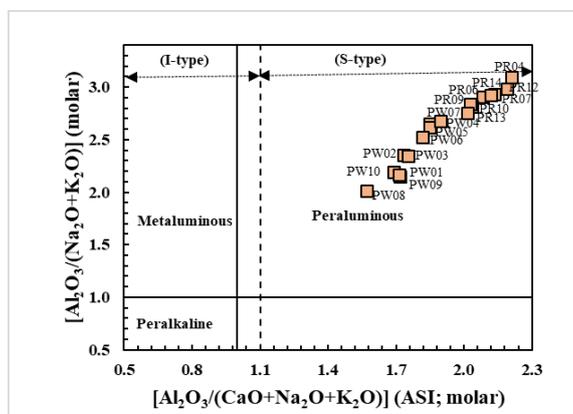


Figure 8 Aluminum saturation indices (ASI) plot of Molar ratios A/NK versus A/CNK discriminant diagram for the Phrao-Wiang Pa Pao Granites.

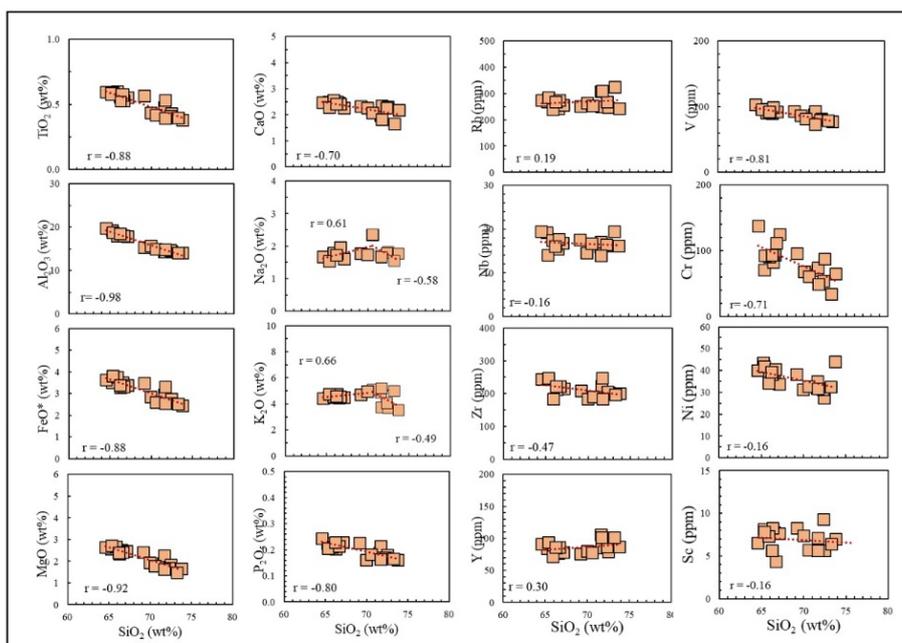


Figure 9 Harker variation diagrams for some major element oxides and trace elements of the Phrao-Wiang Pa Pao Granites.

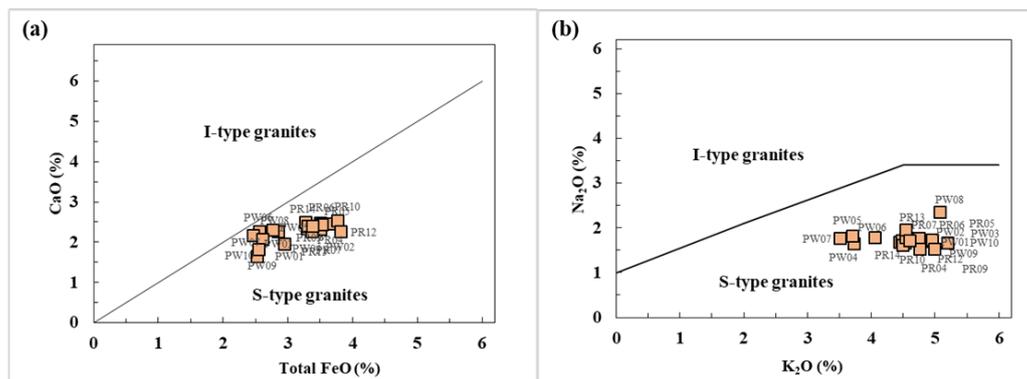


Figure 10 The discrimination diagrams of the Phrao-Wiang Pa Pao Granites (a) CaO versus total FeO and (b) Na₂O versus K₂O.

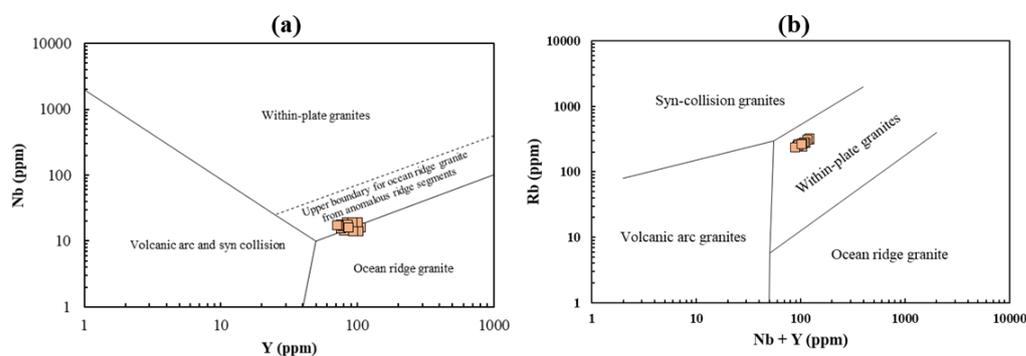


Figure 11 The tectonic discrimination diagrams of the Phrao-Wiang Pa Pao Granites (a) Y versus Nb and (b) (Nb+Y) versus Rb.

Discussion

The least-altered granitic rocks in the Phrao and Wiang Pa Pao areas are granodiorite and monzogranite, based on modal analyses, quasi-chemical constituents, and chemical compositions. The rock samples have a coarse-grained and porphyritic texture and consist of quartz, plagioclase, and potassium feldspar, with minor biotite, muscovite, apatite, zircon, and opaque minerals. The CIPW normative minerals were normative quartz, plagioclase, and orthoclase, with minor corundum, hypersthene, magnetite, ilmenite, apatite, zircon, and chromite. The geochemistry significance is strongly peraluminous, with concentration $Al_2O_3 >$ total alkaline, resulting in excess normative alumina and thus in normative corundum $> 1\%$ (2.10 - 8.19 %). Actual modal corundum cannot coexist with quartz in granite, so typical muscovite appears instead [38]. In addition, the major element oxides data reveal that the Phrao-Wiang Pa Pao granites have a variable composition with moderate-to-high silica and low content of CaO, MgO, TiO₂, MnO, P₂O₅, Na₂O, and Na₂O/K₂O ratios (0.31 - 0.49). It is most likely to have a high-K calc-alkalic affinity. The calc-alkalic to alkali calcic trend points out a transitional character of the granitoids and gradual potash enrichment during crystal differentiation. The presence of well-defined linear relationships of samples in the Harker variation diagrams observed for most of major element oxides and trace elements for the samples suggest the least post-crystallization alteration and co-magmatic origin. The negative correlation of several major and trace elements is occurred as fractional crystallization. The negative correlations of Al_2O_3 -CaO, TiO₂-Fe₂O₃-V, MgO-Fe₂O₃-Cr, and P₂O₅ represent the crystallization of calcic-plagioclase, Fe-Ti oxide,

biotite, and apatite respectively. The positive and negative correlation of K_2O and Na_2O is K-feldspars crystallization. The trace element contents show slightly clear trends in the investigated syn to post-tectonic granite rocks. The tectonic setting of the formation appears to be an S-type granite and is related to an orogenic environment. The S-type granite was supported by the concentration of trace elements such as $Zr > 150$ ppm and $Cr > 45$ ppm. The time of emplacements is the late Triassic period [4]. According to tectonic discrimination diagrams, it might have formed in a post-orogenic environment (post-collisional granite). The emplacement age of granite in this area is late Triassic period that was referred from a nearby pluton (the Mae Suai porphyritic granite; sample number TG-11A) [14]) by the zircon U-Pb dating. The Late Triassic granites in the Phrao-Wiang Pha Phao area were formed in a post-orogenic environment (post-collisional granite) that responded to the thickening crustal collapse during the amalgamation of the Sibumasu with Indochina blocks (**Figure 12**) [4,5,39].

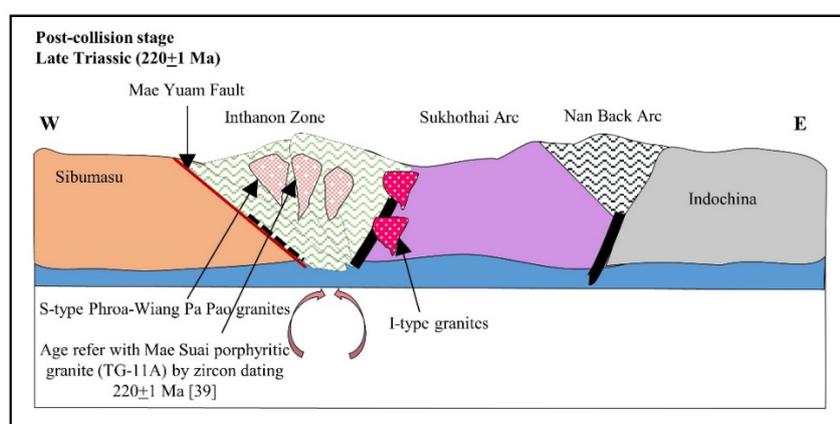


Figure 12 Tectonic setting model (modified from Wang *et al.* [4], Qian *et al.* [5], and Qian *et al.* [14]).

Conclusions

The Late Triassic Phrao-Wiang Pha Phao Granite is granodiorite to monzogranite based on modal analyses, normative minerals, and chemical compositions. The rocks have a coarse-grained and porphyritic texture and consist of quartz, plagioclase, and potassium feldspar, with minor biotite and muscovite. Their whole-rock geochemistry, i.e. the occurrence of normative corundum and the proportions of Na_2O/K_2O , is comparable with that of S-type granites. The studied granitic rock samples mostly have high-K calc-alkaline affinity and peraluminous rock. According to tectonic discrimination diagrams, it might have formed in a post-orogenic environment (post-collisional granite) of the Sibumasu and the Indochina blocks. This research used lithology, major-oxides, and trace elements to nomenclature and identified the geochemical characteristics and tectonic formation. Future research should conduct more REE and age dating investigations that accurate tectonic model interpretation.

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